Effect of DC electric field on longitudinal resistance of two dimensional electrons in a magnetic field.

Jing-qiao Zhang and Sergey Vitkalov*

Physics Department, City College of the City University of New York, New York 10031, USA

A. A. Bykov, A. K. Kalagin and A. K. Bakarov

Institute of Semiconductor Physics, 630090 Novosibirsk, Russia

(Dated: February 6, 2008)

Abstract

The effect of a DC electric field on the longitudinal resistance of highly mobile two dimensional electrons in heavily doped GaAs quantum wells is studied at different magnetic fields and temperatures. Strong suppression of the resistance by the electric field is observed in magnetic fields at which the Landau quantization of electron motion occurs. The phenomenon survives at high temperature where Shubnikov de Haas oscillations are absent. The scale of the electric fields essential for the effect is found to be proportional to temperature in the low temperature limit. We suggest that the strong reduction of the longitudinal resistance is the result of a nontrivial change in the distribution function of 2D electrons induced by the DC electric field. Comparison of the data with recent theory yields the inelastic electron-electon scattering time τ_{in} and the quantum scattering time τ_q of 2D electrons at high temperatures, a regime where previous methods were not successful.

The nonlinear properties of highly mobile two dimensional electrons in AlGaAs/GaAs heterojunctions is a subject of considerable current interest. Strong oscillations of the longitudinal resistance induced by microwave radiation have been found at magnetic fields which satisfy the condition $\omega = n \times \omega_c$, where ω is the microwave frequency, ω_c is cyclotron frequency and $n=1,2...$[1,2]. At high levels of the microwave excitations the minima of the oscillations can reach values close to zero[3,4,5,6]. This so-called zero resistance state (ZRS) has stimulated extensive theoretical interest[7,8,9,10,11,12]. At higher magnetic field $\omega_c > \omega$ a considerable decrease of magnetoresistance with microwave power is found[2,5,6] which has been attributed to intra-Landau-level transitions[13].

Another interesting nonlinear phenomenon has been observed in response to DC electric field[14,15]. Oscillations of the longitudinal resistance, which are periodic in inverse magnetic field, have been found at DC biases, satisfying the condition $n \times \hbar\omega_c = 2R_cE_H$, where R_c is the Larmor radius of electrons at the Fermi level and E_H is the Hall electric field induced by the DC bias in the magnetic field. The effect has been attributed to "horizontal" Landau-Zener tunneling between Landau levels, tilted by the Hall electric field E_H[14].

In this paper we report a new phenomenon. We have observed a strong reduction of the 2D longitudinal resistance induced by DC electric field E_{dc} which is substantially smaller that required for the "horizontal" electron transitions between Landau levels[14,15]. In contrast to the inter Landau level scattering, the observed effect depends strongly on temperature. We suggest that the phenomenon is due to a substantial and nontrivial deviation of the electron distribution function from equilibrium induced by the DC electric field E_{dc}. We find reasonable agreement between our results and a recent theory that considers such an effect in the high temperature limit[12].

Our samples were cleaved from a wafer of high-mobility GaAs quantum well grown by molecular beam epitaxy on semi-insulating (001) GaAs substrates. The width of the GaAs quantum well was 13 nm. AlAs/GaAs type-II superlattices served as barriers, making possible a high-mobility 2D electron gas with high electron density[17]. Two samples (N1 and N2) were studied with electron density $n_1 = 1.22 \times 10^{16}$ m^{-2}, $n_2 = 0.84 \times 10^{16}$ m^{-2}, and mobility $\mu_1= 93$ m^2/Vs, $\mu_2= 68$ m^2/Vs at T=2.7K. Measurements were carried out between T=1.8 K and T=77 K in magnetic field up to 3.2 T on d=50 μm wide Hall bars with a distance of 250 μm between potential contacts. The longitudinal resistance was measured using a current of 0.5 μA at a frequency of 77 Hz in the linear regime. Direct electric current
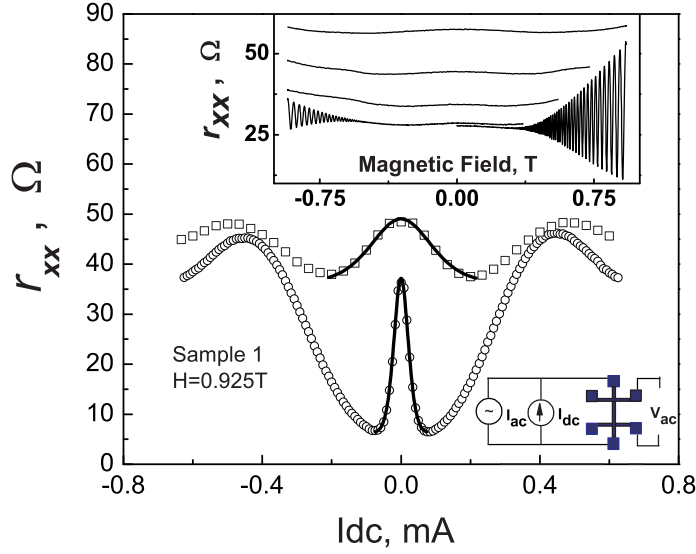
FIG. 1: Dependence of the differential resistance r_{xx} on DC bias at H=0.925T. Cirles correspond to T=4.3 K, squares correspond to T=19.8 K. The solid lines are theoretical curves obtained from Eq. 3. The fitting parameters are I_0=0.055 (mA) and δ=0.334 for T=4.3K and I_0=0.1802 (mA) and δ=0.177 for T=19.8 K. The top inset shows quantum oscillations of the longitudinal resistance at different temperatures T=1.9 K (bottom curve, right), 4.2 K (bottom curve, left), 9.9, 19.8 and 35 K (remaining curves in ascending order). The experimental set-up is shown at bottom right.

(bias) was applied simultaneously with AC excitation through the same current leads (see insert to fig. 1). Although we have studied, strictly speaking, the differential resistance, for the sake of simplicity we will refer to it below as resistance.

Typical curves of the longitudinal resistance r_{xx} as a function of the DC bias are shown in Fig. 1 at two temperatures. At high DC bias the resistance exhibits maxima that satisfy the condition $n \times \hbar\omega_c = 2R_c E_H$, corresponding to "horizontal" transitions between Landau levels[14,15]. Another striking feature is the sharp peak at zero DC bias which broadens as the temperature is raised. This zero bias peak is the main topic of our paper.

The evolution of the magnetoresistance with DC bias and magnetic field is shown in Fig. 2. The zero bias peak appears at relatively high magnetic field $H \approx 0.2 - 0.3$ T (see fig.2a). At these fields the Landau level width $\hbar/\tau_q$ extracted from amplitude of Shubnikov de Haas (SdH) oscillations becomes to be comparable with $\hbar\omega_c$ and the SdH oscillations are visible
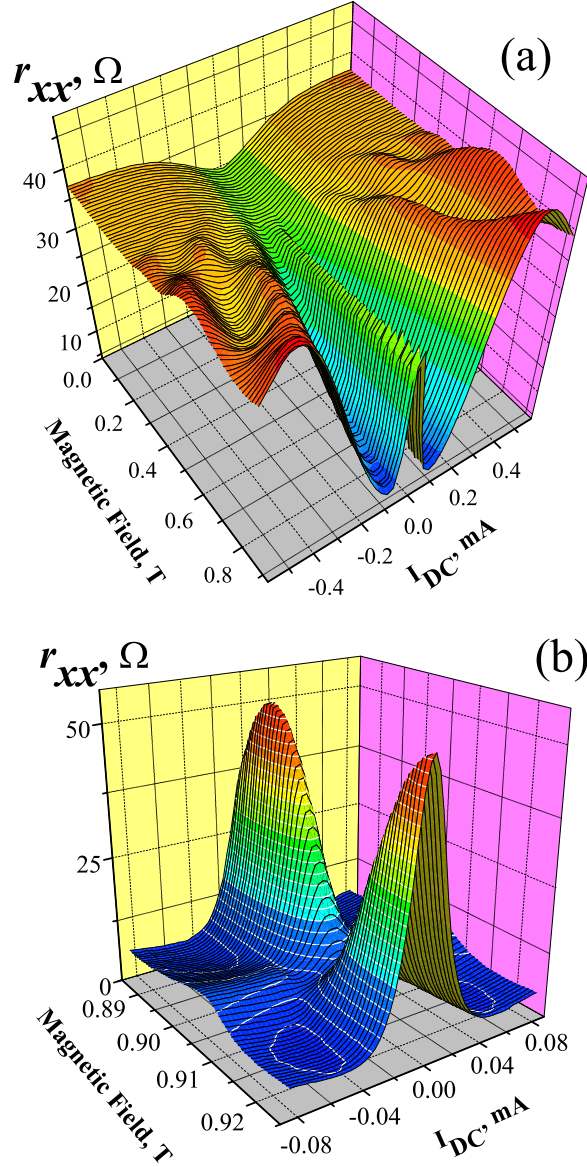
FIG. 2: (a) The differential resistance r_{xx} as a function of magnetic field and DC bias at temperature T=4.3 K. (b) A similar plot at T=1.9 K over a narrower range of the experimental parameters, yielding better resolution.

at low temperatures (see curve at T=1.9K in the top insert to fig.1). The strength of the peak increases gradually with magnetic field. At the zero bias considerable SdH oscillations are present in high magnetic field. The magnitude of the SdH oscillations at T=4.3 K is substantially smaller than the amplitude of the zero bias peak. The peak is still present

at temperatures above T=30K where no SdH oscillations are detected. A better resolved snapshot of the peak evolution is presented in Fig. 2b. The figure demonstrates the effect at low temperatures T=1.9 K, where the SdH oscillations are well developed.

The striking reduction of the resistance by several times is observed at temperatures at which no SdH oscillations are present. This is quite different from what one expects for electron heating by the electric field. As shown in the insert to Fig. 1, the resistance increases for higher temperatures, in contrast with the observed decrease with applied electric field. It should also be noted that at low temperatures, the largest effect possible due to heating is to reduce the resistance from its value at a SdH maximum to the "average" baseline value (which is $\approx$26-28 (Ω) in the insert to Fig. 1). The observed reduction in Fig. 2b is much greater than this indicating a new phenomenon associated with the application of an electric field[16].

From a theoretical perspective, nonlinear phenomena in high mobility 2D electron systems can be conveniently separated into: (a) effects of electric field on the electron distribution function[12], and (b) effects of electric field on the kinematics of electron scattering[8,11]. It was recently realized that the the first of these should provide the dominant contribution to the nonlinear response in 2D electron systems. Below we will compare our results with this approach.[12]

The theory considers 2D electrons in classically strong magnetic field at finite electric field E_{dc} and at relatively high temperature $T \gg \hbar\omega_c$. Due to conservation of total electron energy $\epsilon + eE_{dc}x$ in the DC electric field E_{dc}, the spatial electron diffusion translates into the diffusion of the electrons in energy space. The solution of the diffusion equation in ϵ-space yields nontrivial oscillations of the nonequilibrium electron distribution function with period $\hbar\omega_c$. The amplitude of the oscillations is stabilized by inelastic electron-electron scattering, which is found to be proportional to T^2. Relative to the Drude conductivity, σ_D, in zero magnetic field, the theory predicts a longitudinal conductivity:

$$\Delta\sigma_{xx}/\sigma_D = 2\delta^2[1 - \frac{4Q_{dc}}{1 + Q_{dc}}], \tag{1}$$

where $\delta = exp(-\pi/\omega_c\tau_q)$ is the Dingle factor, τ_q is the quantum scattering time and the parameter Q_{dc} is

$$Q_{dc} = \frac{2\tau_{in}}{\tau_{tr}} (\frac{eE_{dc}v_F}{\omega_c})^2 (\frac{\pi}{\hbar\omega_c})^2. \tag{2}$$

Here τ_{in} is the inelastic relaxation time, τ_{tr} is the transport scattering time and v_F is the Fermi velocity.

In order to compare with experiment, the differential conductivity at frequency ω, $\sigma_\omega = dJ/dE = d(\sigma(E)E)/dE$, is obtained using eq.(1), and the variation of the differential resistance is found to be:

$$\Delta r_{xx}/R_0 = 2\delta^2 [\frac{1 - 10Q_{dc} - 3Q_{dc}^2}{(1 + Q_{dc})^2}], \tag{3}$$

where R_0 is the resistance at zero magnetic field. In a classically strong magnetic field $\omega_c\tau_{tr} \gg 1$, the DC electric field is almost perpendicular to the electric current I_{dc}: $E_{dc} = \rho_{xy}I_{dc}/d$, where d is the sample width. Using Eq. 2, we rewrite the parameter Q_{dc} in the form $Q_{dc} = (I_{dc}/I_0)^2$, where the scale I_0 is a fitting parameter. In accordance with Eq. 3 the parameter I_0 is directly related to the width of the zero bias peak and the peak magnitude is proportional to δ^2. Below we refer to the parameter I_0 as the linewidth. Examples of theoretical fits to the data using Eq.3 are shown by the solid lines in Fig. 1, using δ and I_0 as fitting parameters[18].

The dependence of the width of the peak (I_0) on magnetic field is presented in Fig. 3 at different temperatures. At high temperature the peak width varies considerably with magnetic field. The approximately linear increase of the scale I_0 with magnetic field agrees with the theory. The deviations from the linear dependence are beyond the scope of the theory. The oscillations may be related to magneto-phonon resonances observed in these systems at high temperature[20]. At low temperature, a regime that has not been considered by the theory, the width of the zero bias peak is found not to depend on magnetic field.

For several different temperatures, the insert to Fig. 3 shows the magnetic field dependence of the Dingle parameter, δ, which is obtained from comparison of the magnitude of the zero bias peak with the theory (see Eq. 3). The parameter δ decreases with decreasing magnetic field, and disappears below H=0.2T. Using theoretical expression for the Dingle parameter[12] $\delta = exp(-\pi/\omega_c\tau_q)$, we have plotted the parameter δ vs magnetic field using the quantum scattering time τ_q as a fitting parameter. This is shown in the insert by the solid line. The obtained quantum time $\tau_q =1.5$ (ps) is close to the quantum time extracted from the usual analysis of SdH oscillations at different temperature and/or magnetic field.
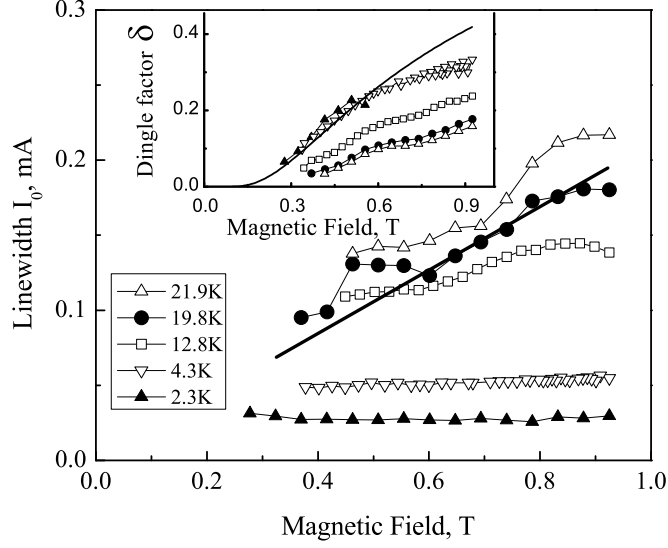
FIG. 3: Dependence of the width of the peak I_0 on magnetic field at different temperatures, as labeled. The solid line represents the linear dependence expected from the theory in the high temperature limit (see Eq. 2). The inset shows the magnetic field dependence of the parameter δ obtained from the fit of the zero bias peak using Eq. 3. The solid line shows the theoretical dependence of the Dingle parameter δ on magnetic field, corresponding to a quantum scattering time τ_q=1.5 (ps).

A comparison between these two results is shown in the bottom insert to Fig. 4. Using this new method the time τ_q is found for temperatures up to 24K, where SdH oscillations are not detectable and previous methods fail to work. Thus the method extends considerably the temperature range, where the quantum scattering time can be studied.

The temperature dependence of the width of the peak is shown in Fig. 4[21]. At low temperatures the width of the peak is found to be proportional to the temperature T. The linear temperature behavior of the I_0 indicates the quadratic temperature dependence of the inelastic scattering time: $\tau_{in} = \alpha/T^2$ (see eq.2), where α is a constant. This is in agreement with the theory[12]. At higher temperature a noticeable sublinear deviation is observed. This can also be captured by the theory if the temperature variations of the transport scattering time τ_{tr} is significant. The temperature dependence of τ_{tr} determined from the resistivity at zero magnetic field is shown in the top insert to the figure. The solid lines in the main figure
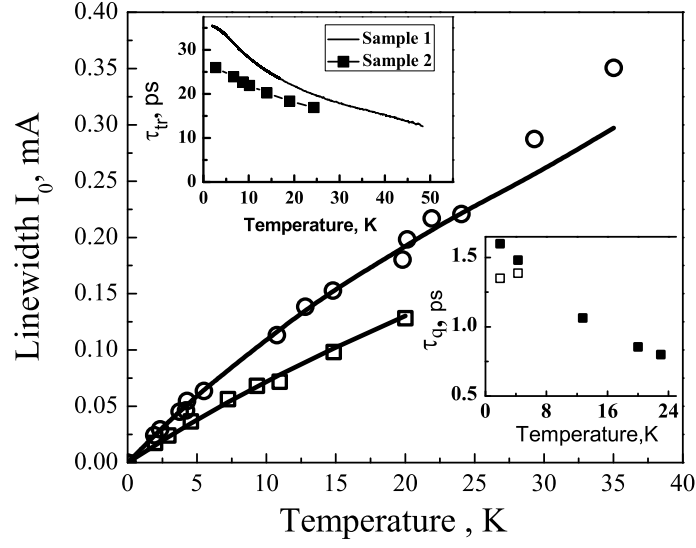
7

FIG. 4: Dependence of the width of the zero bias peak I_0 on temperature for sample N1 (open cirles) and sample N2 (open squares) at H=0.925T. The solid lines are the theory using Eqs. 2 and 3. The comparison gives an inelastic scattering time $\tau_{in} = 10/T^2(12/T^2)$(ns) for sample N1(N2). The top inset shows the transport time τ_{tr} vs temperature at zero magnetic field. The dependence of the quantum scattering time τ_q on temperature is shown in the bottom insert. Open squares correspond to τ_q determined from the amplidute of the SdH oscillations using Lifshits-Kosevich formulae[19]. Filled squares are the τ_q determined by comparison of the amplidute of the zero bias peak with Eq. 3.

are theoretical curves plotted in accordance with eq.2 and eq.3 in which the temperature variations of the τ_{tr} are taken into account and the constant α is the only fitting parameter. For the inelastic time we have found $\tau_{in}^{(1)} = 10 \times 10^{-9}/T^2$ (s) and $\tau_{in}^{(2)} = 12 \times 10^{-9}/T^2$ (s) for sample 1 and 2 . The corresponding theoretical estimations[12] of the inelastic time give $\tau_{in,t}^{(1)} = 4.8 \times 10^{-9}/T^2$ (s) and $\tau_{in,t}^{(2)} = 3.2 \times 10^{-9}/T^2$ (s). We consider this as satisfactory agreement, in light of several approximations used in the theory. The somewhat larger values of the inelastic time τ_{in} obtained in the experiment could also be due to additional electron screening of 2D electrons by X-electrons in AlAs/GaAs type-II superlattices[17]. At high temperature $T > 30$ K a considerable super-linear temperature dependence of the linewidth is found (not shown for sample N2). This phenomenon has been left for a future study.

In summary, a strong reduction of the longitudinal resitivity of 2D electrons in classically strong magnetic fields is observed in response to DC electric field. We have found that the effect is not related to Joule heating even at temperatures down to 2K, where strong quantum oscillations (SdH) are present that are highly sensitive to the temperature. At low temperature (2-10K), the scale of the electric fields at which the effect occurs is proportional to the temperature. Reasonable agreement is established with recent theory[12] that has predicted significant and nontrivial variations of the electron distribution function in response to a DC electric field. The comparison with the theory allowed us to find inelastic electron-electron scattering time τ_{in} and the quantum scattering time τ_q of the 2D electrons at high temperatures where previous methods, based on analysis of quantum oscillations, fail.

Acknowledgments

* Corresponding author: vitkalov@sci.ccny.cuny.edu

[1] M.A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B **64**,201311(R) (2001);

[2] P.D. Ye, L. W. Engel, D.C. Tsui, J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno, Appl. Phys.Lett **79**,2193 (2001).

[3] R. G. Mani, V.Narayanamurti, K. von Klitzing, J. H. Smet, W. B. Jonson, and V. Umansky, Nature(London) **420**, 646 (2002)

[4] M.A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett **90** 046807 (2003).

[5] S. I. Dorozhkin, JETP Lett. **77**, 577 (2003).

[6] R. L. Willett, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett **93** 026804 (2004).

[7] A. V. Andreev, I. L. Aleiner, and A. J. Millis, Phys.Rev. Lett. **91**, 056803 (2003)

[8] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. **91**, 086803 (2003)

[9] P. W. Anderson and W. F. Brinkman, cond-mat/0302129

[10] J. Shi and X. C. Xie, Phys. Rev. Lett. **91**, 086801 (2003).

[11] M. G. Vavilov and I. L. Aleiner Phys. Rev. B **69**, 035303 (2004)

[12] I. A. Dmitriev, M.G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B **71**, 115316 (2005).

[13] S. I. Dorozhkin, J. H. Smet, V. Umansky and K. von Klitzing Phys. Rev. B **71**, 201306(R) (2005).

[14] C. L.Yang, J. Zhang, and R. R. Du, J. A. Simmons and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002)

[15] A. A. Bykov, Jing-qiao Zhang, Sergey Vitkalov, A. K. Kalagin, and A. K. Bakarov Phys. Rev. B **72**, 245307 (2005)

[16] The actual (not differential) resistance is 12.7 Ohm at DC bias I_{dc} =0.08 mA and H=0.92T in Fig.2b. This is considerably below the baseline value: average between resistances at maximum and nearest minimum ($\approx$26-28 Ω).

[17] K. J. Friedland, R. Hey, H. Kostial, R. Klann, and K. Ploog, Phys.Rev.Lett. **77**, 4616 (1996).

[18] Although the theory is developed in high temperature limit, we have used the formula (2) and (3) to find width of the peak and it's amplitude at all temperatures. Other fitting functions (procedures) do not change significantly the results presented in fig.3 and fig.4.

[19] T. Ando, A. B. Fowler and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[20] A. A. Bykov, A. K. Kalagin, and A. K. Bakarov JETP Lett.**81**, 523 (2005).

[21] Using energy relaxation rate $1/\tau_\epsilon$ measured in GaAs/AlGaAs (see "E. Chow *et al* Phys. Rev. Lett. **7**, 1143 1996) we have estimated the electron temperature at DC biases relevant to the zero bias peak. Negligibly small electron overheating by the DC biases is found: $\Delta T \approx 0.1K$ at T=4.2K and $\Delta T \approx 0.01K$ at T=10K